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RESIDUAL ACCELERATION DATA ON IML-1: DEVELOPMENT OF A DATA REDUCTION AND DISSEMINATION PLAN

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1. Introduction

The need to record some measure of the low-gravity environment of an orbiting space vehicle was recognized at an early stage of the U.S. Space Program. Such information was considered important for both the assessment of an astronaut's physical condition during and after space missions and the analysis of the fluid physics, materials processing, and biological sciences experiments run in space. Various measurement systems were developed and flown on space platforms beginning in the early 1970s. Similar in concept to land based seismometers that measure vibrations caused by earthquakes and explosions, accelerometers mounted on orbiting space vehicles measure vibrations in and of the vehicle due to internal and external sources, as well as variations in a sensor's relative acceleration with respect to the vehicle it is attached to. The data collected over the years have helped to alter the perception of gravity on-board a space vehicle from the public's early concept of zero-gravity to the science community's evolution of thought from microgravity to milligravity to g-jitter or vibrational environment.

Since the advent of the Shuttle Orbiter Program, especially since the start of Spacelab flights dedicated to scientific investigations, the interest in measuring the low-gravity environment in which experiments are run has increased. This interest led to the development and flight of numerous accelerometer systems dedicated to specific experiments. It also prompted the development of the NASA MSAD-sponsored Space Acceleration Measurement System (SAMS). The first SAMS units flew in the Spacelab on STS-40 in June 1991 in support of the first Spacelab Life Sciences mission (SLS-l). SAMS is currently manifested to fly on all future Spacelab missions, including the IML, USML, and USMP series, and on at least one mid-deck mission a year.

This aggressive schedule means that an inordinately large amount of accelerometer data will be collected in the upcoming years. The first three flights of SAMS (SLS-l, STS-43, IML-l) collected several gigabytes of data. Foreseeing the need for an organized approach to dealing with such amounts of data, the Center for Microgravity and Materials Research (CMMR) at the University of Alabama in Huntsville contracted with NASA (NAG8-759) to assess the sensitivity of typical low-gravity experiments to the vibrational environment of orbiting space laboratories, to determine the interest of experiment principal investigators in analyzing acceleration data in conjunction with their experimental results, and to develop an acceleration data processing plan that could be used for the analysis of large accelerometer data bases.

The initial stages of work on the contract involved the assessment of experiment sensitivity to Orbiter-type residual accelerations. The results of this work are discussed in previous reports. Sections 2-5 discuss progress through the 7th semi-annual period. Section 2 discusses our data processing efforts. This includes the development of an Acceleration Data Analysis Guide which investigators can use to assess their need for accelerometer data, and the development of a Pattern Recognition Visualization Database (PRIDE) system that can be used to characterize and classify large quantities of accelerometer data. Section 3 discusses our implementation of data processing techniques on existing flight acceleration data bases and section 4 highlights our dissemination of information about processing techniques and the low-gravity environment of earth orbiting laboratories through various publications and participation in numerous conferences. In section 5 we discuss our application of the data processing guide to the IML-1 mission. Section 7 lists areas of continuing work.

2. Data Processing

Our initial approach to accelerometer data analysis was to investigate established methods of time series and spectral analysis to see which were most applicable to the large data bases resulting from Orbiter missions. Our research eventually led to two related development projects: the Acceleration Data Analysis Guide and the Pattern Recognition Visualization Database (PRIDE) system. In general, the former is intended as a pre- and immediate post-flight aid to investigators of low-gravity experiments in assessing their need for accelerometer data and specific data analysis techniques. The latter applies the techniques of pattern recognition, data visualization, data base systems, time series and spectral analysis, and expert systems to the problem of characterizing and classifying Orbiter accelerations. The PRIDE system can be used to interpret the acceleration environment during an individual mission, and will ultimately be used to create an overall classification of acceleration signatures for various missions with similar configurations.

The Acceleration Data Analysis Guide is discussed in detail in several references[1,2] and included in Appendix A. The guide consists of three main sections of questions meant to prompt investigators into analyzing their data access and data processing needs. Part A pertains to the location and timing of a low-gravity experiment scheduled to fly on an Orbiter mission. Part B identifies times during the mission when an experiment may experience potentially intolerable accelerations and when the experiment may have increased sensitivity to accelerations. The information provided can be used before the mission to identify sections of accelerometer data that may be of interest to in investigator. Post-flight selection of data segments is based on the responses to Part C which addresses the experiment tolerance to quasi-steady accelerations and vibrational excitation (g-jitter).

Upon selection of data windows of interest, detailed analysis may follow an investigator's individual processing plan, either based on the PI team's knowledge of data analysis techniques or prompted by the Acceleration Data Analysis Guide. While such analysis should be confined to limited segments of data which interest PIs, it is also necessary to analyze an entire set of accelerometer data to assess the Orbiter low-g environment. The PRIDE (Pattern Recognition Visualization Database) system applies the techniques of pattern recognition, data visualization, data base systems, data analysis, and expert systems to the problem of characterizing and classifying the acceleration environment on-board orbital laboratories.

Both supervised and unsupervised pattern recognition techniques are incorporated into the PRIDE system. Supervised pattern recognition uses human knowledge of data to aid in classification while unsupervised pattern recognition does not. In the PRIDE system, the supervised pattern recognition aspects are primarily achieved through the application of various data visualization techniques to raw acceleration data and various transformations of the raw data, such as vector magnitudes and Fourier transforms. Additional supervision will be possible through use of the CLIPS expert system.[3] This allows the increasing expertise of the system users to be stored in the data base via CLIPS.

Unsupervised pattern recognition in PRIDE is achieved through the use of the ISODATA algorithm. This algorithm is typically used to classify data for which there is no known classification. This algorithm will be applicable to the acceleration data base directly by an operator, and will also be available for controlled use by a specially written CLIPS shell. This will make it possible to have ISODATA running without human intervention. Additionally, an ergodic search technique has been developed which identifies the location and duration of high energy acceleration events. Notably, this technique offers refined control of the application of Fourier techniques by providing information about when a potentially interesting acceleration event starts and what length data window to select for spectral analysis.

Data visualization is used not only in supervised pattern recognition as discussed above, but it is also used for general evaluation of the data character. Analysis of the data character leads to a clearer understanding of the nature of the problem and should lead to the development of new approaches to acceleration analysis. Note that this use of data visualization is independent of the supervised pattern recognition support function.

A relational data base has been installed on the CMMR Stardent computer system and has been fully integrated with all the functions of PRIDE. Use of this common data base form will enhance the transport of PRIDE to other platforms. Additionally, the use of a data base provides several advantages over flat file formats, for example data integrity, maintainability, and large data base manipulation.

The manipulation of large data bases is achieved through the application of various data reduction techniques. Two main data reduction techniques used are vibration windowing and ergodic windowing. Vibration windowing is used to identify and select windows which fit the definition of a damped high magnitude oscillatory vibration. Ergodic windowing identifies and selects windows based on a measure of the energy attributes of a portion of the accelerometer time series. These provide a way to make the processing of such huge data bases more practical. Additionally, the use of two independent techniques makes the resulting classification more dependable.

3. Implementation on Existing Data Bases

The majority of our developmental work was done using accelerometer data collected during the 1985 Spacelab 3 (SL3) mission with a Bell Miniature Electro-Static Accelerometer (MESA) package. This data set was collected at a sampling frequency of 300 Hz with a nominal 50 Hz lowpass filter applied. The data were telemetered for ground-based storage and processing. We obtained requested segments of the data set in engineering format on VAX tape from John Scott of NTI, based at NASA MSFC.

Different time series and spectral analysis techniques were tested on both VAX 11/785 and Stardent Titan computers. Processing routines were written in FORTRAN for the VAX, accessing IMSL subroutine libraries. On the Titan, the commercially available mathematical processing software Matlab was used. The use of different computer systems and different analysis structures gave us some indication of the variation in processing time that will be experienced by investigators. Initial work on the PRIDE system was done on the VAX, but, except for initial data transfer, the C-based PRIDE system runs on the Titan, taking advantage of that computer's graphics capabilities.

During the development of the Acceleration Data Analysis Guide, we obtained an overview of the low-gravity environment of Columbia and the Spacelab during SL3. In general, we recognized that the dominant frequency components excited during the mission were related to Orbiter and Spacelab structural modes. This was suggested by earlier work by Hamacher and others[4,5] and has been supported by more recent analysis of SAMS data. We discuss the low-g environment of SL3 in several publications listed in the following section.

The Acceleration Data Analysis Guide was used to plan our processing of the Honeywell In-Space Accelerometer data collected during STS-32 in January 1990. This instrument and the resulting data are discussed in the literature.[6,7] We are currently writing a paper discussing our processing of the data, including spectral analysis not reported elsewhere.[8] In general, we can say that these data show the familiar pattern of structural mode excitation. STS-32 was not a Spacelab mission, so modes related to the Spacelab structure and support system are not seen in these data as they are in Spacelab mission data. Of particular interest in this data set is the presence of treadmill induced accelerations which are now being compared to SAMS data collected during similar activity.

We have also done some limited analysis of SAMS data from the SLS-1 mission. Again, these data show the dominance of structural modes in the frequency domain. There is an expected difference in time history magnitudes among different missions and among different sensor locations on the same mission. This is caused by localized vibration sources, different payloads, and different levels of scheduled crew activity. In general, however, acceleration magnitudes tend to be in the 10^{-4} to 10^{-3} g range during sleep and normal crew activity periods. Primary thruster firings and OMS burns cause accelerations on the order of 10^{-2} g. Absolute maximum magnitudes of these thrust related events are not known because accelerometer saturation levels are exceeded. The structural modes which can be excited by both localized, internal sources and external sources are at frequencies less than 10 Hz.

4. Publications and Conferences

During the last six-monthly period, numerous papers were published in refereed journals and presented at professional conferences and NASA Microgravity Measurement Group meetings, covering our main topics of study: experiment sensitivity in a low-gravity environment, the development of data processing techniques, and the application of processing techniques to accelerometer data bases.

5.1 Publications

Alexander, J. I. D., Low-gravity Experiment Sensitivity to Residual Acceleration: A Review, Microgravity Sci. Technol. III (1990) 52.

Rogers, M. J. B., J. I. D. Alexander, and R. S. Snyder, Analysis Techniques for Residual Acceleration Data, NASA TM-103507, July 1990.

Rogers, M. J. B. and J. I. D. Alexander, Analysis of Spacelab 3 Residual Acceleration Data, J. Spacecraft and Rockets 28 (1991) 707.

Rogers, M. J. B. and J. I. D. Alexander, Residual Acceleration Data Analysis for Spacelab Missions, Microgravity Sci. Technol. V (1992) 43.

5.2 Conferences

Rogers, M. J. B. and J. I. D. Alexander, A Strategy for Residual Acceleration Data Reduction and Dissemination, Adv. Space Res. 11 (1991) (7)5, 28th COSPAR Plenary Meeting, July 1990, The Hague, The Netherlands.

Rogers, M. J. B. and J. I. D. Alexander, Cross-correlation Analysis of On-orbit Residual Accelerations in Spacelab, AIAA Paper 91-0348, AIAA 29th Aerospace Sciences Meeting, January 1991, Reno, Nevada.

Rogers, M. J. B., Development of a Residual Acceleration Data Reduction and Dissemination Plan, Inter. Workshop on Vibration Isolation Technol. for Microgravity Sci. Applications, April 1991, NASA LeRC.

Rogers, M. J. B. and J. I. D. Alexander, Experiment Specific Processing of Residual Acceleration Data, AIAA Paper 92-0244, AIAA 30th Aerospace Sciences Meeting, January 1992, Reno, Nevada.

Rogers, M. J. B., J. I. D. Alexander, and J. Schoess, Detailed Analysis of Honeywell In-space Accelerometer Data - STS-32, presented at 29th COSPAR Plenary Meeting, September 1992, Washington, DC.

Wolf, R., M. J. B. Rogers, and J. I. D. Alexander, A Data Base Management System for Residual Acceleration Data, presented at 29th COSPAR Plenary Meeting, September 1992, Washington, DC.

6. IML-1 Processing

As part of our analysis of experiment sensitivity, we identified several IML-1 principal investigators with potentially sensitive experiments. These experiments are listed below. • CAST - Casting and Solidification Technology

- TGS - Triglycine Sulfate Crystal Growth from the Melt
- PCG - Protein Crystal Growth
- MICG - Mercuric Iodide Crystal Growth
- VCGS - Growth of Mercuric Iodide Crystals from Vapor
- GPPF - Plant Physiology Facility
- CPF - Critical Point Facility
- OCGP - Organic Crystal Growth of Proteins

We contacted the investigator teams for each of these experiments prior to the launch of IML-1. Each team was sent a copy of our Acceleration Data Analysis Guide which we completed to the extent of our knowledge of their experiment. We suggested that completion of the guide questions would be advantageous, if there was interest in analyzing their experiment results in conjunction with accelerometer data. We received positive comments from a few of the investigator teams and are currently working with the CAST team to identify possible acceleration events during critical times of that experiment and with the TGS PI to provide acceleration information and data.

7. Areas of Future Work

Much work remains to be done before a complete characterization of the low-gravity environment of the shuttle Orbiters is accomplished. The low-g community is headed in the right direction. There is increasing concern about potential noise (vibration) sources in the

Orbiters and in individual experiments. Several organizations have extensive vibration isolation technology development projects in the works that should be tested in the near future. Communication among groups flying accelerometer systems has increased due in large part to the NASA Microgravity Measurement Group. The resulting exchange of results and data should have a significant positive effect on Orbiter characterization. Experiment investigators are becoming more interested in processing accelerometer data in conjunction with their experimental results. We consider this the most important step in the low-g analysis process at this point because it will clarify the sensitivity estimates derived from ground based experiments and computer modelling of experiments. Ultimately, we predict that a thorough understanding of the low-g environment of the Orbiters and of experiment sensitivity to vibrational disturbances will be a key element in the success of low-gravity experimentation on-board Space Station Freedom.

7. References

[1]Rogers, M. J. B. and J. I. D. Alexander, Residual Acceleration Data Analysis for Spacelab Missions, **Microgravity Sci. Tech.** V (1992) 43.

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Appendix A

ACCELERATION DATA ANALYSIS GUIDE

This package is an **Acceleration Data Analysis Guide** to help low-gravity principal investigators assess their need for accelerometer data and form an acceleration data processing plan. The guide consists of three sections. Part A pertains to the location and timing of an experiment. Part B identifies times during the mission when an experiment may experience potentially intolerable accelerations and when the experiment may have increased sensitivity to accelerations. The answers provided can be used before a mission to identify sections of accelerometer data that may be of interest to an investigator. Post-flight selection of data segments is based on the responses to Part C which addresses the experiment tolerance to quasi-steady accelerations and vibrations (g-jitter). The information needed for **Part A** pertains to the location and timing of an experiment. This information is obtained from various mission documents. Because of the complex orbiter structure, accelerometer data should be obtained from the accelerometer closest to the experiment. Accelerometers on a mission may include:

- Those flown as part of an experiment (it is possible an investigator will share the data)

- MSAD sponsored Space Acceleration Measurement System (SAMS) units (contact Dick DeLombard, the SAMS Project Manager, NASA LeRC; or Gary Martin, NASA HQ, for information on requesting SAMS units and SAMS data)

- the Orbiter Experiments Program's High Resolution Accelerometer Package (HiRAP), Aerodynamics Coefficient Identification Package (ACIP), and Orbital Acceleration Research Experiment (OARE) systems (contact Bob Blanchard, NASA LaRC, for information).

It is important to know in what form the residual acceleration data are collected and stored and what type of pre-processing and filtering is applied. Different systems save different forms of data, based on experiment sensitivities, computer storage and processing capabilities, and other factors. [1-12] Available data may include acceleration data in g units, counts, or other units such as volts or amps that need to be converted to g. Other possibilities include mean acceleration values, peak acceleration values, or RMS acceleration values for given windowing lengths. Data should also be corrected for any errors related to temperature variations, sensor bias, and other factors. [13-17] The above information should be available from the accelerometer designer or manufacturer.

The major goal of this processing guide is to allow an investigator to select a minimum amount of accelerometer data to analyze. The data selected should include acceleration information pertinent to an experiment. Some time slices of data can be identified as interesting before and during the mission. Such times are identified in Part B of the data sheet. The responses to Parts B and C depend on the investigator's understanding of the experiment sensitivity to different acceleration levels. The first question of **Part B** addresses the possibility that an experiment will be more sensitive to acceleration variations during certain stages of the experiment. For example, protein crystal growth experiments exhibit increased sensitivity during the nucleation phase. The times that these stages occur should be catalogued by the investigator team during the mission, because experiment activity will not exactly follow the pre-mission timeline.

Question two of Part B addresses the timing of potentially intolerable acceleration sources during the experiment run. Acceleration sources include experiment equipment, Orbiter maintenance equipment (pumps, fans, etc.), crew exercise, and RCS firings for Orbiter attitude adjustments. Again, while this type of activity may be included in pre-mission timelines, it is best to record the times of acceleration sources that may be of interest when they occur. Note that some Orbiter systems activity is recorded in the MSFC Calibrated Ancillary System which may be available for some missions through ACAP. A growing number of references in the literature provide an idea of the acceleration levels related to various sources and the Orbiter structural modes excited during typical mission activity. [1-12,18]

Part C of the data analysis guide allows the investigator to note the quasi-steady acceleration and vibration levels to which an experiment will be sensitive. Particular frequencies at which the experiment has increased sensitivity should also be noted. Experiment tolerance limits can be obtained from previous runs of the experiment in reduced gravity environments, or from computer modelling of the experiment. This information can be used in both time and frequency domain threshold detection routines to further limit the acceleration data base.

The use of a threshold detection routine should give some indication of the appropriateness of the sensitivity limits used. If the limits are exceeded the majority of the time, an initial look at the experimental results should indicate whether the acceleration environment was too severe for the experiment or whether the tolerance limits were too strict. Similarly, if the limits are rarely exceeded, analysis of the experimental results should indicate whether the sensitivity limits used were too relaxed or whether the acceleration levels were low enough for a successful experiment run. Based on such information, sensitivity limits should be modified for future flights of the experiment.

ACCELERATION DATA ANALYSIS GUIDE

PART A - General experiment and accelerometer information

(Indicate start and end times of multiple runs, if appropriate)
EXPERIMENT START TIME (MET):
EXPERIMENT END TIME (MET):
EXPERIMENT RUN TIME:
EXPERIMENT LOCATION:

CLOSEST ACCELEROMETER UNIT TO EXPERIMENT, OR ACCELEROMETER UNIT OF INTEREST (LOCATION AND TYPE):

ACCELEROMETER DATA SAMPLING RATE:

NUMBER OF ACCELEROMETER DATA POINTS PER AXIS TO BE COLLECTED DURING EXPERIMENT (To compute the amount of accelerometer data to be collected during the experiment, multiply the accelerometer sampling rate by the length of the experiment. For example, for the extent of a ninety hour experiment, 3.24×10^7 accelerometer data samples would be collected at a sampling frequency of 100 samples per second.):

ORIENTATION OF PRIMARY EXPERIMENT AXES WITH RESPECT TO ORBITER STRUCTURAL AXES (The orientation of the experiment may be important if it has axes of increased or decreased acceleration sensitivity. Accelerometer data can be manipulated to analyze acceleration levels in a particular direction.):

PART B - Identification of specific times of interest

TIMES/REASONS OF KNOWN INCREASED EXPERIMENT SENSITIVITY:

TIMES OF POTENTIAL ACCELERATION SOURCES DURING THE EXPERIMENT (scheduled orbiter attitude adjustment, crew exercise periods):

PART C - Thresholding information for post-flight data selection

FREQUENCY AND MAGNITUDE RANGES OF INTEREST:

MAXIMUM TOLERABLE CONTINUOUS (STEADY) ACCELERATION:

MAXIMUM TOLERABLE (TRANSIENT) ACCELERATION:

EXPERIMENT SENSITIVITY TO CHANGES IN ACCELERATION ORIENTATION:

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Appendix B: Published papers and papers submitted for publication

M. J. B. Rogers and J. I. D. Alexander

Residual Acceleration Data Analysis for Spacelab Missions

Materials processing and life sciences experiments are being conducted in earth orbiting laboratories to take advantage of the reduced gravity environment of space. Accelerometer data are collected during low-g missions to describe the acceleration environment, but the amount collected per mission is overwhelming (on the order of gigabytes). Different research goals, sensor types, and processing techniques make it difficult to compare acceleration data plots from different missions. In particular, spectral representations of data differ widely. Specific structural modes are known for the orbiter and Spacelab from engineering models and ground tests, but a complete characterization of primary and secondary acceleration sources has not yet been compiled.

We have developed a two level reduction plan that will allow investigators to create limited, user specific accelerometer data bases that can be used in post-flight experiment analysis and orbiter characterization. First level processing uses our knowledge of experiment sensitivity to identify times when tolerable acceleration levels are exceeded. Together with a preliminary analysis of experiment results, this enables the experimenter to identify particular time intervals which require more detailed processing. Second level analysis centers on acceleration time histories (magnitude and orientation) and frequency components. Data decimation is introduced as a means for reducing the amount of data that must be processed while analyzing a given time window. Cross-correlation analysis is discussed; it is useful in post-flight experiment analysis for assessing causal relationships between residual accelerations and experimental responses. The ability to identify and process limited windows of acceleration data will further the acceleration environment characterization process and will be essential in revising the design, location, and use of low-gravity experiment equipment for future missions.

1 Introduction

In recent years, low-gravity experimenters have shown increased interest in obtaining residual acceleration data to use in pre-flight modelling and post-flight processing of their experiments. The object of many low-gravity materials processing and life sciences experiments is to study physical and biological phenomena in space under drastically reduced acceleration conditions relative to the steady $9.8\ \mathrm{ms}^{-2}$ ($1\ g$) acceleration experienced on the earth's surface. Because some of these experiments are sensitive to even small magnitude accelerations [1–5], it is necessary to characterize the time-dependent acceleration environment in order to properly interpret the experimental results. To date, one of the major factors that have prevented investigators from accessing residual acceleration data for post-flight experiment analysis and orbiter characterization is the vast amount of data that results from a typical orbiter mission. Even for a sampling rate as low as 12.5 Hz, on the order of 10^6 samples per axis can be expected from a seven day low-gravity mission.

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In the following section, we discuss residual acceleration measurements that have been reported in the literature and suggest reasons for the differences in magnitude among the various data bases. In sect. 3, we introduce various aspects of the orbiter characterization process and in sect. 4 we present several specific techniques that investigators can use in the post-flight processing of residual acceleration data and experimental results.

2 Residual Acceleration Data

Measurements of residual acceleration have been collected during several orbiter missions with a variety of instruments [6–13]. The resulting data, supplemented by the simulation of orbiter attitude motion accelerations, have provided us with a general idea of the low-gravity environment aboard an orbiter during a typical mission. Specific acceleration sources, however, are still difficult to characterize. In general, three categories of residual accelerations are experienced in orbiting space laboratories: quasi-steady, transient, and oscillatory [9, 14]. The quasi-steady accelerations are related to the earth's gravity gradient, spacecraft attitude and altitude, and atmospheric drag. They have frequencies on the order of the orbital frequency (10^{-4} Hz) and magnitudes in the 10^{-9}–$10^{-6}\,g$ range [9, 12, 14]. $10^{-6}\,g$ accelerations have been recorded using specialized accelerometer systems such as HiRAP [13], but these quasi-steady accelerations have yet to be successfully identified in data recorded with conventional systems because of instrument limitations and the relative strength of higher magnitude and higher frequency accelerations [15].

These higher magnitude, higher frequency accelerations constitute the other categories of residual accelerations. Transient accelerations can have magnitudes as large as $10^{-2}\,g$ and tend to vary considerably in orientation, but such disturbances are rarely sustained for more than a fraction of a second [11]. These accelerations can be caused

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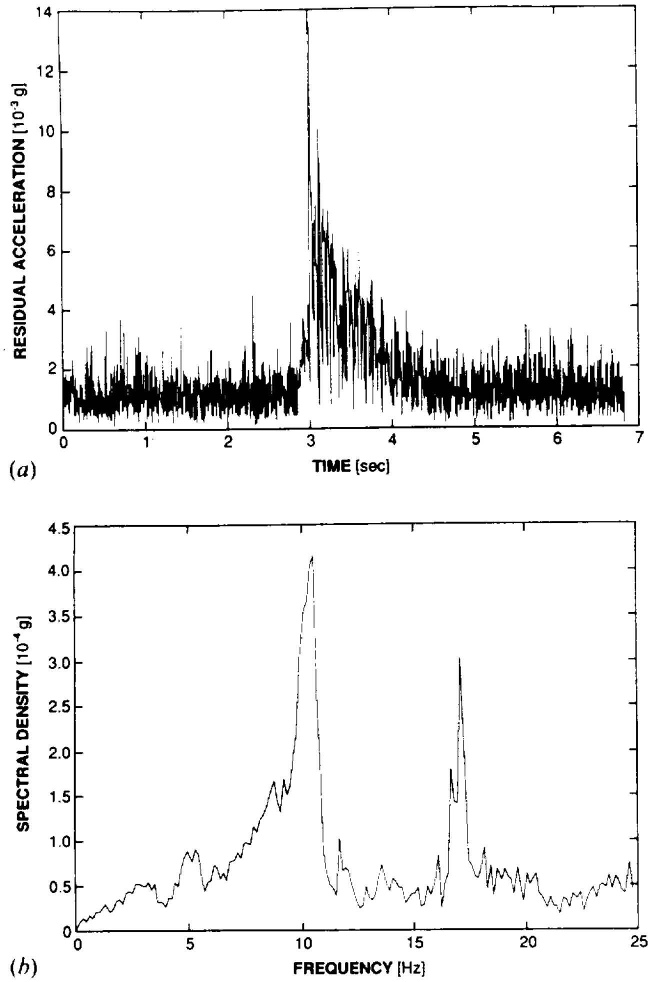


Fig. 1. Window of accelerometer data collected during the SL3 mission (Bell Miniature Electro-Static Accelerometer, $f_s = 300$ Hz, nominal 50 Hz lowpass filter). The disturbance was probably caused by a thruster firing or a local acceleration source within the Spacelab; (a) acceleration vector magnitude; (b) combined spectral density for the three recording axes. Note frequency components at 5, 12, and 17 Hz

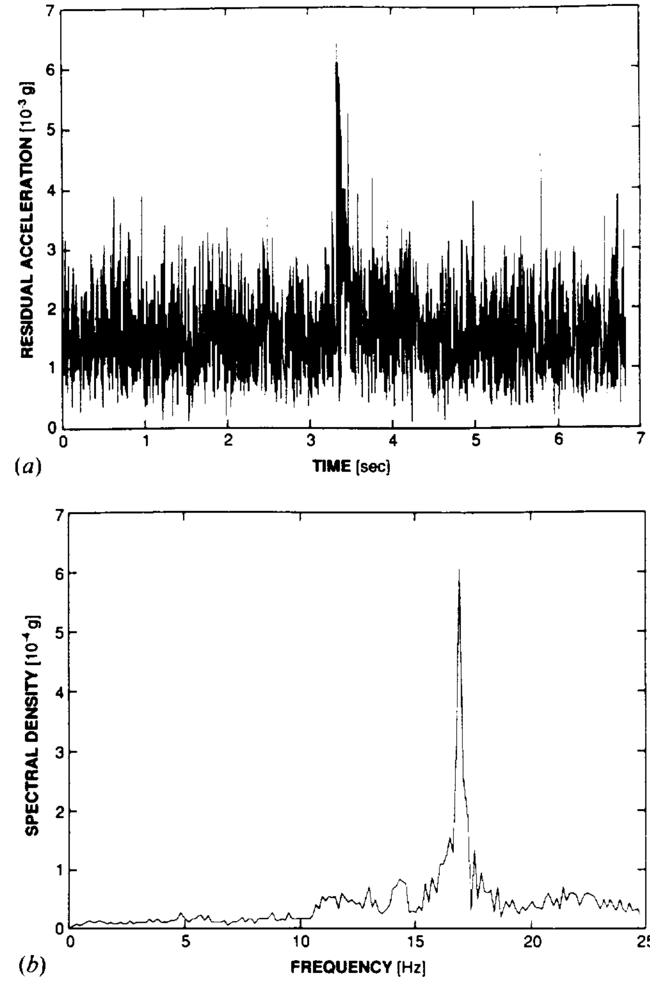
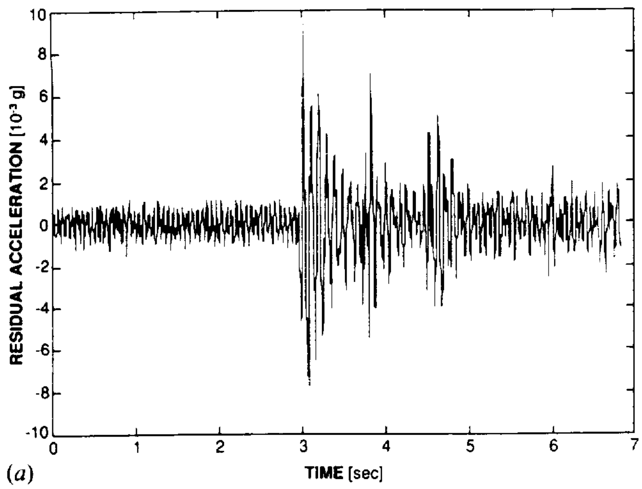


Fig. 2. Window of accelerometer data from SL3 probably caused by crew activity within the Spacelab; (a) acceleration vector magnitude; (b) combined spectral density for the three recording axes. Note the dominant 17 Hz component

by both crew related and operational activities (figs. 1 and 2). Oscillatory accelerations have magnitudes comparable to transient accelerations (10^{-5}–$10^{-3}\,g$), fluctuate rapidly in orientation, and are experienced over a broad range of frequencies for longer times. Recorded oscillatory accelerations are generally related to machinery vibrations and rotations and to structural modes of the orbiter excited by both transient and oscillatory sources. Frequency domain analysis of one second to fifteen minute long windows of *Spacelab 3* (SL3) acceleration data indicates that, from $5 \cdot 10^{-3}$–50 Hz, transient and oscillatory accelerations have amplitude spectra with maximum magnitudes no greater than $10^{-3}\,g$, figs. 1b and 2b [11, 15].

When comparing acceleration measurements from different missions, it is important to note that few accelerometer systems have the same characteristics. Because of different research goals, sensor types, electronics, sampling rates, processing techniques, instrument locations, and other factors, comparisons among residual acceleration data plots presented in the literature are often difficult. The sampling rate, especially, can cause an appreciable magnitude difference among various sets of data [12]. Higher frequency data are constructively added to lower frequency data when high sampling rates are used. This results in overall higher magnitude readings than obtained with lower sampling rates. Similarly, analog filtering performed as part of the data collection scheme, as well as post-flight digital filtering, can result in different magnitude levels for different data sets (see fig. 3).

The use of different processing techniques results in a variety of data presentation styles that may initially appear comparable. Time history plots vary considerably, however, and may include plots of individual axes of data, acceleration vector magnitude, RMS values, and integrated data. In addition, the data presented may be regularly sampled data, peak value data, or some specialized form of data [6–12]. Representations of residual acceleration data as a function of frequency can also take a variety of forms [15–18]. Most



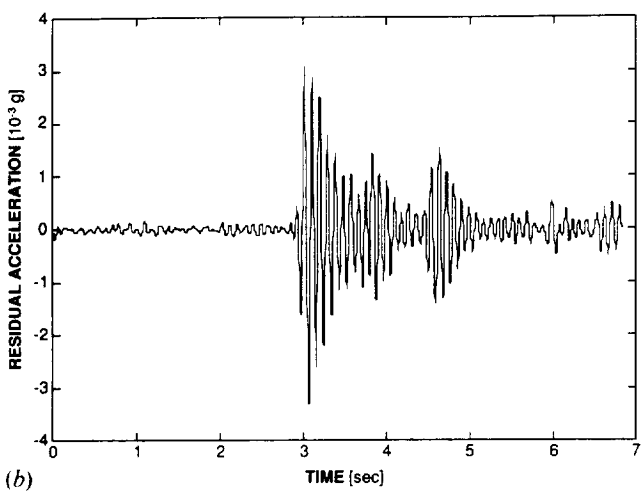


Fig. 3. Differences in magnitude level result from the use of different sampling rates and/or filter cut-offs; (a) window of SL3 accelerometer data (y-axis of fig. 1); (b) same data window with 13 Hz lowpass filter applied. Note difference in magnitude between two plots

common are the amplitude and power spectral densities (see sect. 4.2). If an investigator is only interested in the identification of dominant frequency components, then any type of spectrum is adequate. Meaningful comparisons of component magnitudes among various plots or between spectra and sensitivity plots, however, require a standardized spectral density format.

Instrument location is another important factor involved in comparative data analysis. Data collected near a dominant acceleration source (motors, fans, areas of high crew activity) will show higher overall acceleration levels than data collected with an equivalent system located at a distance from such sources. Some interest has been expressed by low-g investigators in evaluating the propagation of accelerations from known sources through various structures of an orbiter [19]. This is an important factor in orbiter characterization, and in the identification of especially noisy systems and appropriate sites for low-gravity experiments.

Table 1. Orbiter natural frequencies, after Cooke et al. [12]

natural frequency	*structure*
0.43 Hz	cargo bay doors
0.57 Hz	cargo bay doors
0.86 Hz	cargo bay doors
1.2 Hz	cargo bay doors
1.5 Hz	cargo bay doors
2.1 Hz	radiators
2.4 Hz	radiators
3.5 Hz	fuselage torsion
	wing and fin bending
5.2 Hz	fuselage first normal bending
7.4 Hz	fuselage first lateral bending

3 Orbiter Characterization

Limited attempts have been made to date to construct a characterization of the low-gravity environment of the shuttle orbiters [6–11, 15]. Specific structural modes are known for the orbiter and Spacelab from engineering modelling and ground testing (see table 1) [9, 12, 19, 20]. The excitation of these modes has been identified in residual acceleration data as associated with thruster firings and crew activity within the Spacelab [7, 9, 11, 12, 15].

Both orbiter and Spacelab structural modes exist around 5 Hz and 7 Hz [9, 12]. A 12 Hz component observed in the data represents an orbiter structural mode excited by shuttle operations [12]. A ubiquitous 17 Hz signal, present in accelerometer data recorded by different systems, represents another orbiter structural mode as well as the dither frequency of the KU band communications antenna [11]. Figs. 1 and 2 show the presence of these specific frequency components in SL3 data.

A difficulty that will continue to hamper orbiter characterization attempts is that no acceleration source acts alone. Orbiter maneuvers involve the firing of multiple thrusters in a sequence of pulses, and experiment manipulation involves the handling of various pieces of equipment. These transient acceleration sources occur in addition to the back-

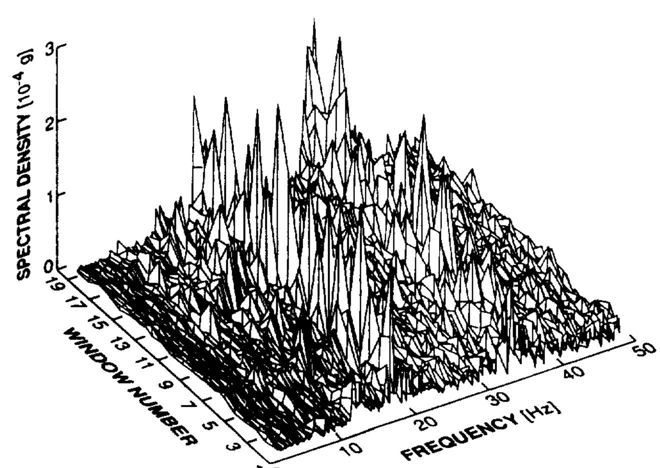


Fig. 4. Spectral densities of twenty successive SL3 time windows. Note varying strengths of 5 Hz, 12 Hz, 17 Hz, and 34 Hz components

ground accelerations related to numerous mechanical systems active during a mission. Fig. 4 shows the dynamic nature of the Spacelab environment. The spectral densities of twenty successive time windows are shown. It can be seen that, while there are dominant frequency components consistently present, the relative strengths of specific components vary over time.

The active environment of the orbiting laboratory does not mean, however, that the task of orbiter characterization is impossible. Through a sequence of ground-based and in-space tests of the response of specific structures to known acceleration sources, we can eventually construct a catalogue of characteristic accelerations and acceleration levels in particular areas of the space laboratory [19, 20]. A knowledge of the acceleration environment to be expected during a mission and of the acceleration levels expected in specific locations in an orbiter will allow the development and siting of future experiments to best utilize or avoid specific aspects of the low-gravity environment.

4 Post-flight Data Analysis

As stated earlier, one of the major obstacles encountered in the analysis of residual acceleration data is the amount of data resulting from a single mission. Gigabytes of accelerometer data are expected from most flights of the NASA *S*pace *A*cceleration *M*easurement *S*ystem (SAMS). In an attempt to effectively manage these data, we have developed an analysis plan that will allow principal investigators of low-gravity experiments to create limited, user specific data bases. The limited data base can be efficiently used in post-flight processing of experimental results. We are also analyzing various processing techniques that may be useful for more detailed residual acceleration data analysis. Two of these techniques, data decimation and cross-correlation analysis, are discussed later in this section.

4.1 Creation of Limited, User Specific Data Bases

In order to create user specific data bases, investigators must have some knowledge of the sensitivity of their experiments to the residual accelerations expected during flight. Such knowledge can be gained from pre-flight modelling of the experiment or from preliminary runs of the experiment in low-gravity conditions (drop-towers, sounding rockets, parabolic flights, orbital flights). Post-flight analysis of experimental results in conjunction with residual acceleration data will also be easier if appropriate experiment parameters are recorded during the experiment.

Our suggested approach to the reduction of residual acceleration data invokes a two level plan that uses sensitivity limits and preliminary experimental results. The plan is outlined in table 2. Pre-flight identification of acceleration sensitivity of a particular experiment will determine acceleration frequency and magnitude ranges of interest and experiment tolerance limits [1]. Particular times when the experiment is most likely to be affected by residual accelerations can also be identified prior to the mission. This includes increased experiment sensitivity during certain stages (e.g., protein crystal growth during the nucleation stage) and expected experiment response to certain timelined mission operations (e.g., thruster firings and crew exercise periods). Preliminary post-flight analysis of experimental results will allow the investigator to identify times when unexpected results occurred that may be related to perturbations in the residual acceleration environment of the laboratory.

Table 2. Outline of data reduction plan

Level One
1. Pre-flight identification of acceleration sensitivity to determine frequency and magnitude ranges of interest and experiment tolerance limits.
2. Pre-flight identification of times at which the experiment is liable to be most vulnerable, i.e., some experiments may be most sensitive at specific stages (e.g. protein crystal growth during the nucleation stage).
3. Preliminary post-flight analysis of experimental results to identify times when unexpected results occurred that may be related to perturbations in the residual acceleration environment of the laboratory.
Level Two
1. Selection of time windows of interest using a threshold detection routine based on sensitivities identified in Level One, Step 1 above.
2. Use of data decimation techniques, when appropriate, to reduce the number of data points needed to evaluate lengthy windows of data.
3. Specific analysis of windows of data identified in Level One and first step of Level Two, including estimation of mean and mean squared values, determination of the acceleration vector orientation, and spectral analysis to investigate the magnitude of the frequency components for the specific time window of interest.
4. Evaluation of accelerometer data in conjunction with experimental results to identify causal relationships and revise sensitivity limits.

The second level of the data reduction plan involves the actual limitation and processing of the residual acceleration data base using the results of level one. A simple threshold detection routine can be used to identify times when the acceleration magnitude is greater than defined sensitivity limits. Windows of interest can also be selected based on the experiment and mission timelines and preliminary post-flight analysis. Timelines will indicate when sensitive stages of an experiment are scheduled and when potentially intolerable mission events such as orbiter maneuvers are to occur.

4.2 General Processing Techniques

We have found that three main features of residual acceleration data can be used to characterize the acceleration environment of an orbiting space laboratory: the magnitude, direction, and frequency components of the residual accelerations in a given window. Time history information can be used to identify maximum and mean accelerations recorded per axis as well as various other statistics. The

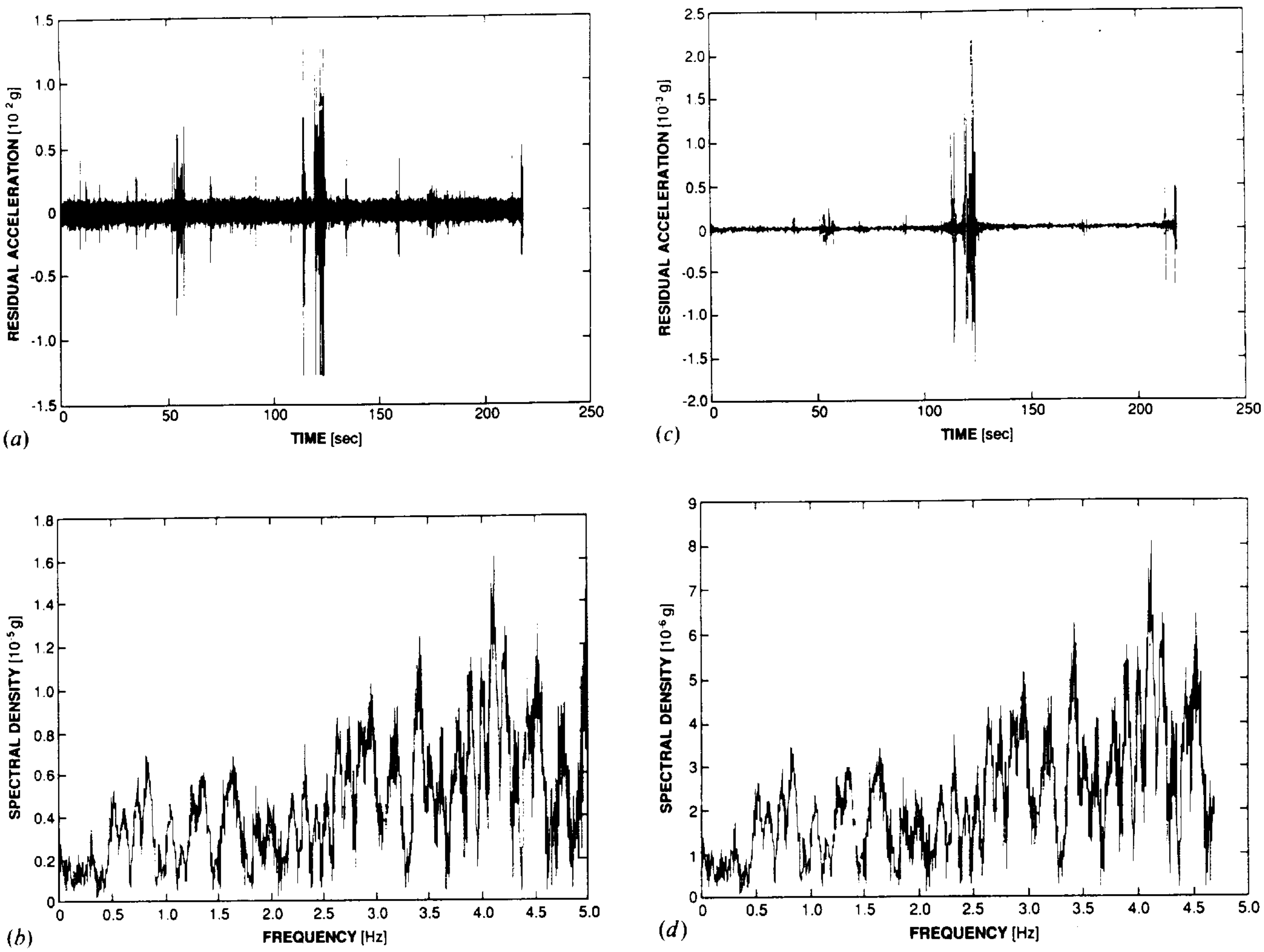


Fig. 5. Example of data decimation; (a) original SL3 time series of 65,536 points (218 s); (b) spectral density of (a); (c) time series decimated 16 times – 5 Hz lowpass filter applied; (d) spectral density of (c). Note decrease in magnitude from original series to decimated series

orientation of a residual acceleration vector can be estimated using direction cosines which give an indication of the angle between a measured acceleration and the recording axis. Because of the number of acceleration sources present in the orbiter and the nature of oscillatory accelerations, the orientation of the residual acceleration vector tends to fluctuate with time [11]. See [16] for more details about evaluating residual acceleration magnitudes, orientations, and frequency components.

The frequency components of a window of residual acceleration data are computed using the Fourier transform. The spectral density obtained for a time series using Fourier analysis indicates the frequencies of the sine and cosine terms that make up the signal being studied. The spectral density of an axis of residual acceleration data a_λ is:

$$A_n = \frac{1}{N}\sum_{\lambda=1}^{N} a_\lambda \mathrm{e}^{-i2\pi n\lambda/N} \tag{1}$$

where N is the number of points in the data window.

For the time period considered, the spectral density at a given frequency is an average of the components of a_λ that have that frequency and has the dimensions of an acceleration [16–18].

The power spectral density of a window of data can be computed by:

$$P_n = 2TA_n^2 \tag{2}$$

where T is the length of the data window in time units.

The power spectral density has dimensions of [(units of original data)^2/Hz] and indicates the power or energy present in the series per unit frequency interval. The square root of the area under the power spectral density plot for a given frequency interval represents the RMS value of the input time series in that frequency range [12, 16, 17].

Comparisons of spectral plots in the literature may be difficult because of differences in software involving scaling factors and definitions of spectra [17, 18]. The two spectra discussed above are generally referred to as *densities* because they refer to a unit frequency interval. The use of a particular spectral representation often depends on the type of numerical analysis an investigator has planned. Because of the rather straightforward representation provided by eq.

(1), we advocate the use of this form. This spectrum gives frequency component magnitudes in units of acceleration. Most experiment sensitivity curves published to date are in the form of acceleration versus frequency, allowing ease of the comparison for the time periods concerned [1]. In addition, the spectral density of eq. (1) can be mathematically converted to a power spectral density by eq. (2).

4.3 Data Decimation

Because of the high sampling rates used in the collection of residual acceleration data, detailed analysis is often limited to a minute or less of data. If an investigator is interested in processing long blocks of data (more than several minutes for sampling frequencies on the order of 100 Hz), an additional tool that can be used to limit data is data decimation, which reduces the sampling rate [18, 21–23]. Like any other data processing technique, some amount of caution must be practiced when decimating data, especially so that higher frequency data are not aliased into the lower frequency region of interest.

Fig. 5 gives an example of data decimation applied to a window of SL3 accelerometer data. The original time series (fig. 5a) is 65,536 points long and has a maximum value of $1.28 \cdot 10^{-2}\,g$. The spectral density of this series out to 5 Hz is shown in fig. 5b. Fig. 5c shows the same window after the data were decimated 16 times; a 5 Hz lowpass filter was applied. This process reduced the number of points to 4,096, while maintaining the temporal coverage of 218 s. Note, however, that the maximum acceleration level represented has decreased to $2.5 \cdot 10^{-3}\,g$. This occurs because the user has no control over data point selection – the sampling is periodic and the original extrema are not necessarily selected. The values of the spectral density of the decimated data are also decreased compared to the original spectrum. The general character of the data is maintained in both the time and frequency domains, so the impact of the decreased magnitudes on the post-flight analysis of accelerometer data depends on the specific needs of the investigator.

4.4 Cross-correlation Analysis

We are interested in analyzing the results of experiments run in a low-g environment. Cross-correlation techniques are generally used to determine the equivalence of time histories and to determine temporal relationships among time series. This appears to be, for specific experiment classes, a viable means of assessing causal relationships between residual accelerations and experimental responses to these accelerations. This analysis method is useful not only in situations where experiments are sensitive to high magnitude, transient accelerations, but also when experiments are most sensitive to oscillatory disturbances [24].

The cross-correlation of two time series can be written as:

$$\phi_{12}(\tau) = \int_{-t_s}^{t_s} f_1(t) f_2(t+\tau)\,\mathrm{d}t \tag{3}$$

where f_1 and f_2 are two zero-mean series and τ is a time lag.

A normalized cross-correlation function is used when the time series considered are of different dimensions and/or comparisons are to be made among different sets of results. The normalized cross-correlation function is [17]:

$$\varrho_{12}(\tau) = \frac{\phi_{12}(\tau)}{[\phi_{11}(0)\phi_{22}(0)]^{1/2}}. \tag{4}$$

The maximum value of the normalized cross-correlation function is unity, which indicates that the two time series considered are identical at the given lag; values close to zero indicate that there is very little similarity between the two series. Positive normalized cross-correlation values close to unity indicate good correlation and negative values with magnitudes close to unity indicate good correlation but with the series out of phase.

While the cross-correlation function between two time series can be estimated directly using eqs. (3) and (4), it can be estimated more efficiently by calculation of the cross-power spectrum:

$$\Phi_{12}(\omega) = F_1^*(\omega) F_2(\omega) \tag{5}$$

where F_1 and F_2 are the spectral densities of f_1 and f_2 and a superscript * denotes complex conjugation.

The cross-power spectrum and cross-correlation function form a Fourier transform pair, so one can be easily obtained from the other. Estimation of the cross-correlation function of two series using the cross-power spectrum affords a factor of $N/4p$ savings of computation time where $N = 2^p$ is the length of the time series considered [22].

The application of cross-correlation techniques to the analysis of low-gravity experiments requires an experiment time history which represents parameters affected by variations of the low-gravity environment. Pre-flight modelling of experiments will enable the investigator to identify appropriate parameters to record. In the case that such a parameter cannot be recorded quantitatively, modelling may also be used to determine typical experiment responses to be used in the creation of experiment time series for cross-correlation analysis [1–5, 24].

5 Summary

Investigators running experiments in the reduced gravity conditions of space need to be able to characterize the time-dependent acceleration environment in order to properly interpret their results. Characterization of the orbiter acceleration environment to date has identified some orbiter and Spacelab structural modes (table 1 and figs. 1–4) [9, 12, 19, 20].

Because the amount of accelerometer data resulting from a typical Spacelab mission is on the order of gigabytes, we have introduced a data reduction and analysis plan with which investigators can merge pertinent segments of residual acceleration data into the post-flight analysis of their experiments. The two level data reduction plan is easily tailored to an investigator's needs based on mission and experiment timelines and information about the experiment sensitivity to accelerations. The first level of the plan involves identification of pertinent experiment time windows to study and the second level involves analysis of these windows. General data processing techniques that can be

used include the analysis of time history statistics, acceleration vector magnitudes, and the orientation of the acceleration vector with respect to a set of coordinate axes. Analysis of frequency components can be achieved through spectral analysis, but we urge that caution should be practiced when comparing different spectral representations (figs. 1–4).

Data decimation can be used to limit the amount of data an investigator should process for post-flight experiment analysis. The reduced acceleration levels resulting from decimation may restrict the usefulness of this technique, depending on the specific needs of the investigator. Cross-correlation analysis is a viable means of assessing causal relationships between residual accelerations and experimental response to accelerations. This method is useful for experiments sensitive to transient accelerations and to oscillatory disturbances.

As we increase our understanding of the acceleration environment of orbiting space laboratories, we will be better able to design and locate low-*g* experiments to obtain the best results possible. Most experiment sensitivity limits used at present are derived from numerical modelling or order of magnitude estimates. With a knowledge of low-*g* experiment results and the environment in which these results were obtained, we can revise tolerance limits, identify "normal" acceleration levels, and decrease further the amount of accelerometer data that must be accessed by investigators after future missions.

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A RESIDUAL ACCELERATION DATA ANALYSIS AND MANAGEMENT SYSTEM

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ABSTRACT

Efficient analysis, management, and dissemination of large, complex, and sometimes poorly understood residual acceleration datasets obtained from low earth orbit space laboratories is necessary in order to maximize the scientific return from microgravity experiments. In view of the large amounts of data that will be collected in future missions, the need for an organized approach to the reduction, analysis, and dissemination is anticipated. Thus, the development of an acceleration data processing plan was started at the Center for Microgravity and Materials Research. Toward that goal we are developing a data analysis and management system that employs a variety of pattern recognition, database management, Fourier analysis, and vibration and ergodic windowing techniques.

INTRODUCTION

It has been recognized for some time that the low-gravity environment of a low-earth-orbit spacecraft can be used as a laboratory for the study of a variety of physical phenomena under reduced (equivalent) gravity conditions. It has also been recognized that the residual accelerations arising from gravity gradient tides, atmospheric drag, thruster firings, crew motions, etc. are sufficient to cause measurable deviations from "zero-gravity" conditions. The need to measure and record the ever-changing low-gravity environment in order to provide important "environmental" data for the post-flight assessment of low-gravity experiments and the physical condition of astronauts has led to the development of several acceleration measurement systems since the early 1970's. Lately, particularly since dedicated spacelab missions began, the interest in residual acceleration data has increased. Indeed with the now regular use of NASA's Space Acceleration Measurement System

(SAMS), the amount of acceleration data being collected is increasing rapidly. The first three flights of SAMS (SLS-1, STS-43, and IML-1) yielded several gigabytes of data. In response to the need for an organized approach to the reduction, analysis and dissemination of data, an acceleration data processing plan was developed at the Center for Microgravity and Materials Research /1,2/.

We have developed a data base management system to handle the large quantity of residual acceleration data that results from a typical low-gravity Orbiter mission. The system will manage a large, graphic data base in support of supervised and unsupervised pattern recognition /3,4/. Use of pattern recognition techniques allows identification of specific classes of accelerations so that these classes can be easily recognized in any set of acceleration data retrieved from spacecraft accelerometer systems. The data will be partitioned following the ANSI/SPARC model /5/. The entire mission time history will form the internal layer of the model. Data reduction techniques will identify limited time windows of interest. Time and frequency domain representations of these windows will compose the conceptual level of the model. The graphics aspect of the management system includes several data visualization techniques that help the user better understand the nature of the acceleration signal being studied. The data base management system was developed on a UNIX-based Stardent Titan computer and is being tested on Spacelab 3 (SL-3) residual acceleration data. When fully developed, it will be suitable for use with other residual acceleration data bases and will be portable to other UNIX-based workstations.

PATTERN RECOGNITION AND DATA VISUALIZATION SYSTEM

An acceleration data analysis and management system has been developed to serve as the core of future residual acceleration data analysis. The PRIDE (Pattern Recognition Visualization Database system applies the techniques of pattern recognition, data visualization, database systems, data reduction, and expert systems to the problem of characterizing acceleration activity from orbital laboratories.

Both supervised and unsupervised pattern recognition techniques are incorporated into the PRIDE system. Supervised pattern recognition uses human knowledge of data to aid in classification while unsupervised pattern recognition does not. In the PRIDE system, supervised pattern recognition is primarily achieved through the application of various data visualization techniques to raw acceleration data. In addition, these techniques are applied to various transformations of the raw data, such as vector magnitudes and Fourier transforms. Additional supervision will be possible through use of the CLIPS expert system /6/. This allows the increasing expertise of the system users to be stored in the data base through CLIPS.

Unsupervised pattern recognition in PRIDE is achieved through the use of the ISODATA algorithm /4/. This algorithm is typically used to classify data for which there is no known classification. This algorithm will be applicable to the acceleration data base directly by an operator, and will also be available for controlled use by a specially written CLIPS shell. This will make it possible to run ISODATA without human intervention. In addition, an ergodic search technique has been developed which identifies the location and duration of high energy acceleration events. Note that this technique offers refined control of the application of Fourier techniques. For example, information such as the start of a potentially interesting acceleration event, or the optimum length of the data window for spectral analysis, can be readily provided.

Data visualization is used not only in supervised pattern recognition as discussed above, but it is also used for general evaluation of the data character. Analysis of the data character leads to a clearer understanding of the nature of the problem and should lead to the development of new approaches to acceleration analysis. Note that this use of data visualization is independent of the supervised pattern recognition support function.

A relational data base has been installed on the CMMR Stardent computer system and has been fully integrated with all the functions of PRIDE. Use of this common data base form will enhance the transport of PRIDE to other platforms. Additionally, the use of a data base provides several advantages over flat file formats, for example data integrity, maintainability, and large data base manipulation.

The manipulation of large data bases is achieved through the application of various data reduction techniques. Two main data reduction techniques used are vibration windowing and ergodic windowing. Vibration windowing is used to identify and select windows that fit the definition of a damped high magnitude oscillatory vibration. Ergodic windowing identifies and selects windows based on a measure of the energy attributes of a portion of the accelerometer time series. These provide a way to make the processing of such huge data bases more practical. Additionally, the use of two independent techniques makes the resulting classification more dependable.

Expert systems technology is used to provide two basic capabilities. First of all, it is used to make the use of ISODATA more practical. Normal use of ISODATA requires a human operator and, even with data reduction, the data sizes that must be handled in a finite time are still enormous. The use of a CLIPS shell to control the ISODATA algorithm is useful. Second, and more important, the availability of an expert system built into the system with a database form of access to the data will provide in the future (when a complete understanding of the processes involved has been achieved) a way to store this knowledge and use this knowledge to drive the characterization process.

Figures 1-3 give examples of typical screen images that can be obtained using PRIDE. Figure 1 is an example of the 3D-FFT technique applied to a 30 minute acceleration time-series from SL-3. The sample time-series contains 420, 000 datapoints per axis. Visual display of this many data-points, even for this relatively short duration, tends to mask the character of the acceleration and is often not very useful. The 3D-FFT, combined with vibration or ergodic windowing, enables identification and display of acceleration events that fit predetermined specifications (either thresholds or particular patterns). This reduces the amount of data that is actually displayed, while supplying more information than visualization of the time series itself. Fig. 1 displays 3D-FFT information for windows which exceeded specified acceleration thresholds. Each axis represents the acceleration component for each of the x-, y-, and z-directions. For each window, the discrete Fourier transform of the acceleration data for each axis produces a discrete set of frequencies separated by a fixed interval, Δf. Each frequency f_i is connected by a straight line segment to the $f_{i-1} = f_i - \Delta f$ and $f_{i+1} = f_i + \Delta f$. Note that the events in this figure are dominated by accelerations associated with the z-direction. Figure 2 is the standard FFT for one of the event (windows) used to produce Figure 1. Figure 3 is an overlap graph drawn from an ergodic analysis. This graph is produced by using the best window size produced by ergodic analysis to focus attention of a given set of window energy values. Subsequently, an acceleration threshold histogram is selected. The temporal location of all windows with associated energy greater than or equal to the characteristic energy of the threshold are recorded. The time segments associated with these high energy events within the overall time interval are used to determine the number of high energy events occurring at any given time.

SUMMARY

PRIDE is in its initial stages of development. Preliminary results suggest that it will be a useful basis for future acceleration processing strategies. It is currently being used to examine recently obtained SAMS /7/ data as well as Spacelab-3 accelerometer data. Correlation of experiment events with acceleration events as well as general characterization of space laboratory environments can readily be accomplished using organized approaches such as PRIDE. The development of such data processing and dissemination packages combined with NASA's program of acceleration measurements planned under the ACAP /8/ program will enable future low-gravity experiment investigators to obtain a clear description of the residual acceleration conditions prevailing during their experiment.

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FIGURE CAPTIONS

Fig. 1. 3D-FFT representation showing a projection from a 4-tuple ($A_x(f)$, $A_y(f)$, $A_z(f)$, f) to 3-tuples ($A_x(f)$, $A_y(f)$, $A_z(f)$) plotted in 3-D space and linked by lines. Data from a 30 minute high energy event during SL-3.

Fig. 2. Amplitude spectrum for each of the three acceleration components. Data is taken from one of the event windows shown in Fig. 1.

Fig. 3. "Overlap" plot indicates the temporal location of high energy events within the best window length.

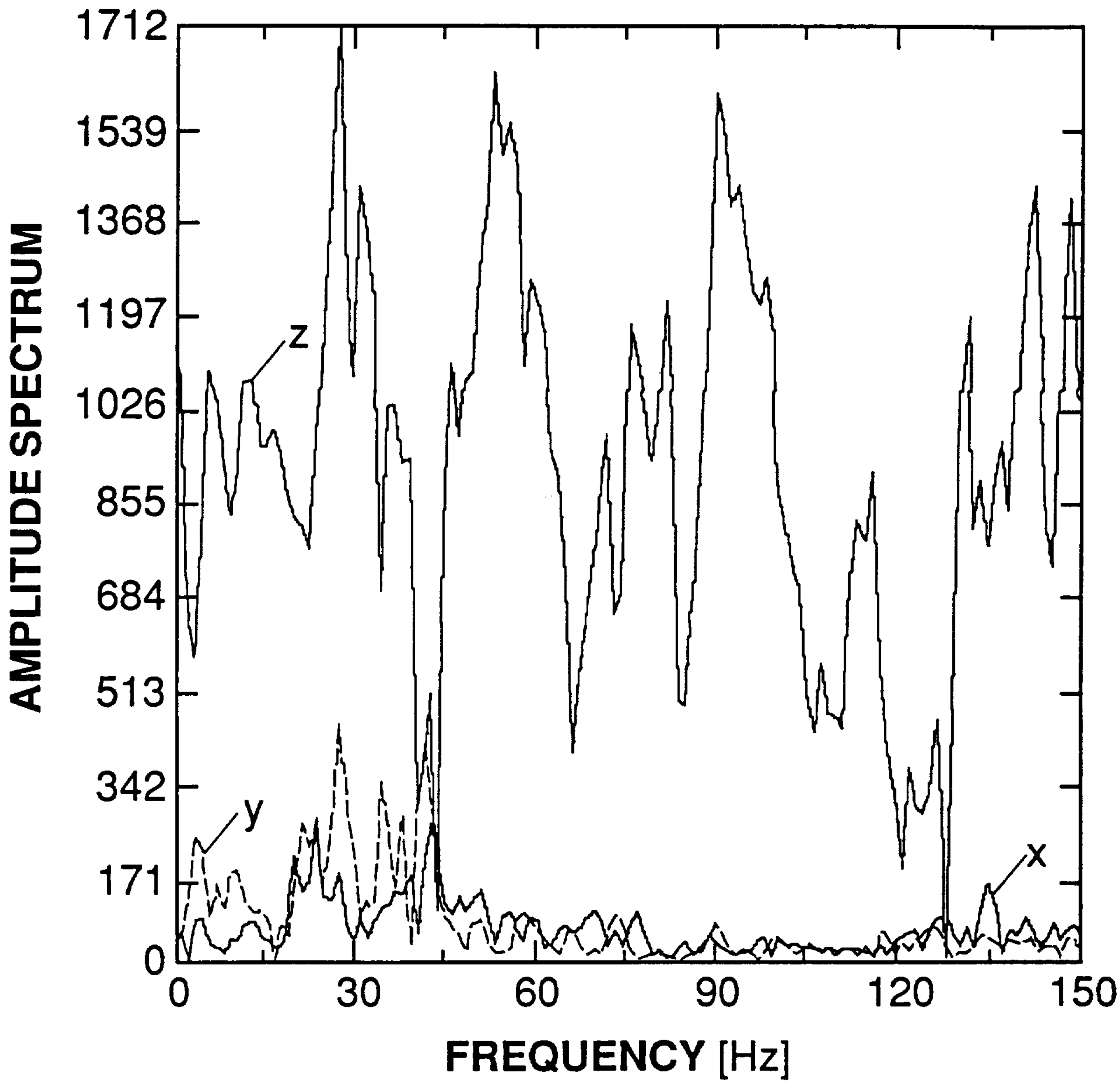
AMPLITUDE SPECTRUM
1712
1539
1368
1197
1026
855
684
513
342
171
0
z
y
x
0
30
60
90
120
150
FREQUENCY [Hz]

FIG. 1

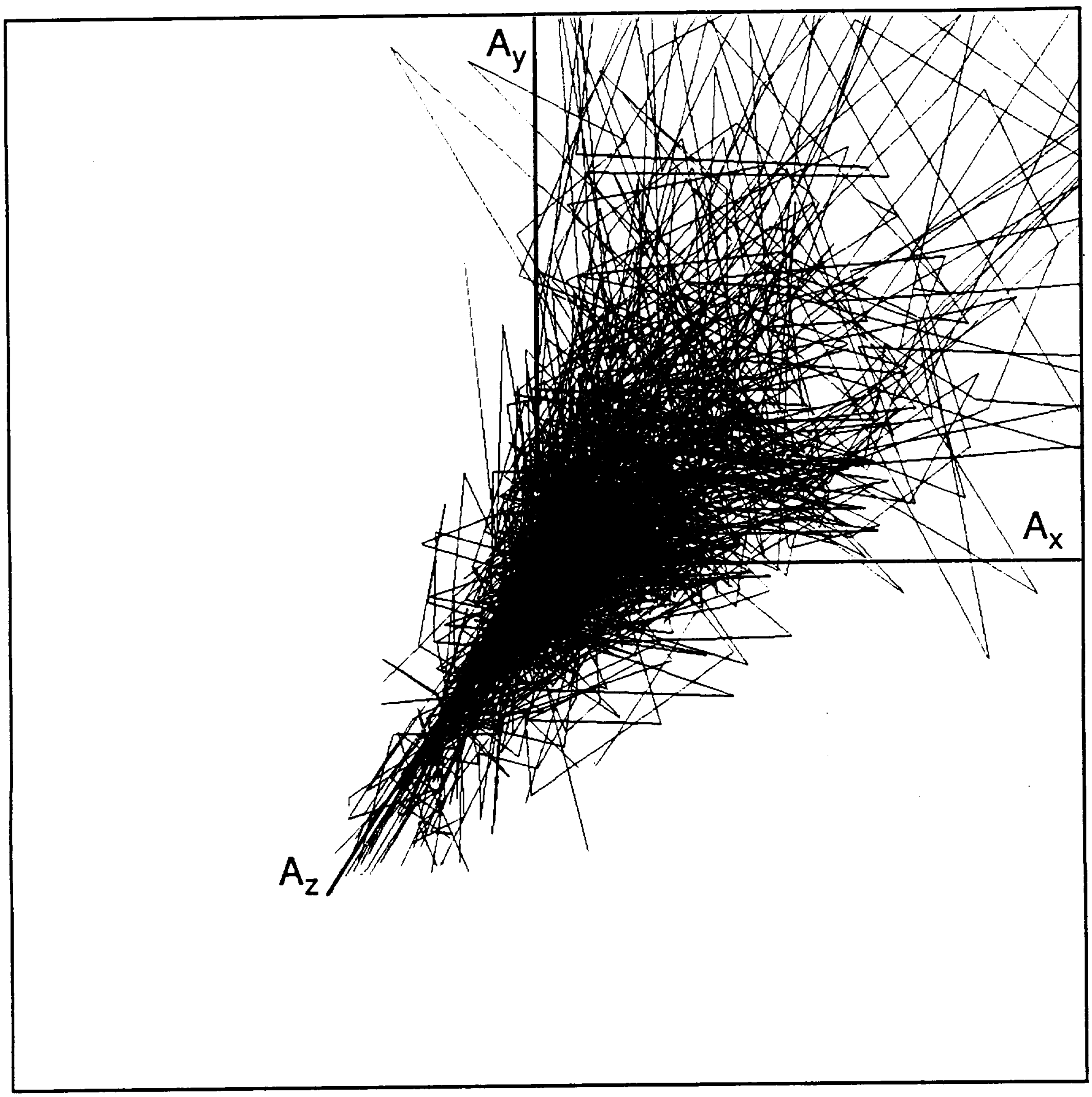

FIG. 2

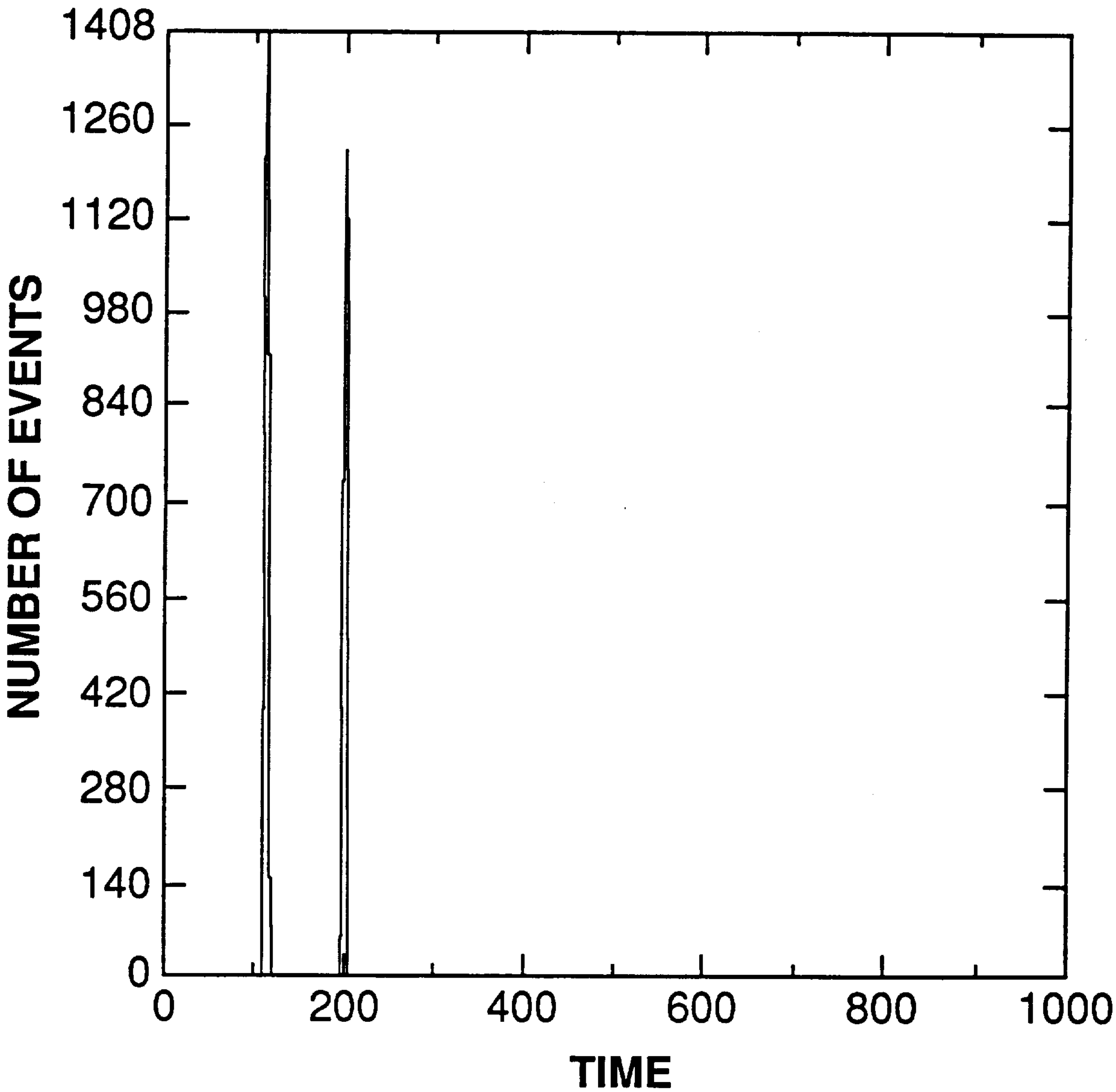
1408
1260
1120
980
840
700
560
420
280
140
0
NUMBER OF EVENTS
0
200
400
600
800
1000
TIME

FIG. 3